Etkins and Epstein (*1*) have suggested that the net discharge of polar ice sheets in the past century, inferred from global sea level rise, may (i) substantially account for observed long-period variations of the earth's rate of rotation by changing the planetary moment of inertia and (ii) substantially affect global mean temperature by means of the latent heat absorbed by melting ice. These suggestions, if verified, have major implications: (i) observed changes in the length of the day could provide a useful measure of polar ice sheet mass balance and (ii) climate model studies of the global temperature trend would require substantial revision.

Etkins and Epstein used the sea level analysis of Emery (*2*), who found a rise of 30 cm per 100 years for the period 1935 through 1975. This result is weighted heavily by the large number of stations on the east coast of the United States, which is a region of known isostatic subsidence. Gornitz *et al.* (*3*) analyzed all tide gauge data available from the Permanent Service for Mean Sea Level, Birkenhead, England, weighting each of 14 geographical regions equally. With all stations of record length 20 years or more included, except several stations in regions of known local subsidence, Gornitz *et al.* obtained a global mean sea level rise of 12 cm in the past 100 years and 10 cm after correction for long-term shoreline movements. To minimize the possibility of bias due to station selection, we repeated the analysis of Gornitz *et al.* (*3*) but included all stations; the result was a 13-cm uncorrected sea level rise in the past 100 years and 10 cm after correction (Fig. 1, curve a). We estimate the uncertainty as ~ 5 cm, due primarily to the difficulty of separating eustatic sea level rise from shoreline movement. Our procedure of averaging trends of all independent regions appropriately weights the data; more formal analysis of the global distribution of sea level change does not provide a more meaningful global trend.

Although a substantial part of the observed sea level rise may be attributable to thermal expansion (*3*), we can obtain an upper limit for the effect of ice sheet melting on the earth's rate of rotation by assuming that the entire rise is due to melting. If we take the sea level rise as being uniformly distributed over the globe and the latitude of the ice as 90°, again maximizing the effect, the sea level rise yields the change of rotation rate shown in Fig. 1, curve b. The observed rotation rate (Fig. 1, curve c) exhibits much larger changes. Munk and Revelle (*4*) have suggested that variable motion in the earth's core may be the principal cause of the variations of rotation rate. Even the slight long-term trend in the observed rotation, more apparent in the 300-year record (*5*), is due largely to tidal friction (*5, 6*). The correlation coefficient between curves b and c in Fig. 1 is 0.0, or −0.3 if the observed change of rotation rate is corrected for tidal friction. We conclude that the melting of ice sheets is not the primary cause of observed variations in the earth's rotation rate during the past century.

An upper limit for global cooling due to polar ice discharge can be estimated by assuming that all 10 cm of the global sea level rise is due to polar ice discharge. The latent heat required to melt this ice is $10 \text{ g} \times 80 \text{ cal g}^{-1} = 800 \text{ cal}$ for each square centimeter of the global ocean. The mean ocean depth mixed at some time during the annual cycle is 125 m (*7*). Thus the global mean cooling would be ~ 0.06°C, for the extreme case in which the discharge occurs rapidly and in which the thermal perturbation is confined to the annual-maximum mixed layer depth. However, any such cooling increases the flux of heat into the ocean [see equation 9 of (*8*)], which tends to negate the cooling effect of ice added at a time earlier than the thermal relaxation time of the ocean surface. This relaxation time is perhaps 5 to 20 years (*3, 8*), but the larger of these values would imply substantial exchange to depths beneath the mixed layer and thus a reduction of the global cooling estimated above. Use of global mean mixed layer depth maximizes the calculated global mean cooling: actually, ice melting occurs at high latitudes where the annual-maximum mixed layer thickness is larger. We conclude that global cooling due to polar ice discharge has not exceeded a few hundredths of a degree centigrade in the past century, and thus this phenomenon does not affect interpretation of global mean temperature trends for this period.

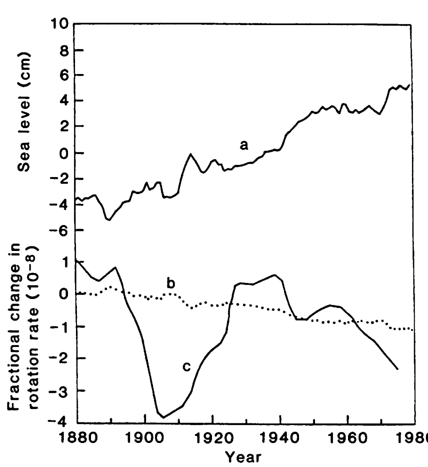

Fig. 1. Five-year mean global sea level trend (curve a) estimated from tide gauge data after correction for long-term shoreline movements. This sea level change, if entirely due to polar ice melting, would cause the change in the earth's rotation rate indicated by curve b for a terrestrial moment of inertia of 8×10^{37} kg m^{-2}. Curve c shows the observed trend of rotation rate (*10*).

Our conclusions that melting polar ice has small effects on global temperature and rotation rate apply to a rate of polar ice discharge of 10 ± 5 cm of sea level per 100 years. However, the effect on rotation will become substantial for a rate of melting several times larger. The location of the pole of rotation may also shift measurably, depending on the geographical source of the melting ice (*6*). The location of melting ice could be accurately measured by satellite monitoring of ice sheet topography (*9*).

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The intent of our report (*1*) was to point out that several seemingly separate geophysical quantities are related to one another through physical processes that may be important in climate change, and to propose that the rise of sea level over the past 40 years is due in part to the net reduction of polar ice. We tried to make the case that some published interpretations of global sea level and temperature records over recent decades are consistent with one another, and with other geophysical quantities, if one makes plausible hypotheses about climate change and the behavior of polar ice sheets. We do not contend that these hypotheses are proven. Neither global mean sea level nor global mean surface air temperatures—let alone the more significant ocean temperatures—are well enough measured that one can with certainty relate one factor to another.

Robock's conclusions are based largely on Paltridge and Woodruff's analysis (*2*) of global surface temperatures. This record suffers from certain inadequacies and questionable assumptions. For example, because of scanty data in many periods and locations and sometimes systematic changes in shipping routes, Paltridge and Woodruff adopted a single invariate pattern of gradients in the sea-surface temperature (SST), on the basis of which they extrapolated data from observation points to preselected grid points.

Because most available records of surface temperature are too heavily weighted to land areas, we speculated (*1*) on how large an excursion of mean SST there might be. We cited Gates *et al.* (*3*) not to assert that "land-based surface air temperature records indicate changes in ocean temperature," as Robock misconstrued, but to argue that wide excursions of land or ocean temperatures do not occur separately: they are not independent. We know from other simulations that much larger changes in land-surface temperatures will result from a doubling of the CO_2 concentration if SST is not so restrained (*4*). Thus, we reason, even if other factors are not held fixed, ocean and land temperatures are strongly linked to one another. This is not the same as saying that one measures the other.

Both Robock and Gornitz *et al.* have analyzed tide gauge station data and have obtained a significantly lower estimate of sea level rise than that obtained by Emery (*5*). In preparing our report (*1*), we did not examine critically Emery's methods nor did we try to derive an independent estimate of the rise of global mean sea level. If Emery's values are positively biased, the problem is much more a result of the lack of sufficient data than of faulty analysis.

Gornitz *et al.* (*6*) also had to face the problem of scarce data. For example, they gave equal weight to a group of 32 relatively reliable stations on the east coast of the United States and two stations along the entire perimeter of Africa (one station on a volcanic island). None of these analyses of global mean sea level can be regarded as definitive. Nevertheless, on the basis of their own estimate that the extent of sea level rise has been minimal, Hansen *et al.* argue that the calculated amount of ice discharge is insufficient to account for the observed changes in the earth's rotation rate. It is true that the temporal variability of the earth's rotation rate does not correlate with the sea level trend, and this is most notable during the period 1895 to 1925. The prominent excursion (deceleration) of the rotation rate and subsequent recovery at that time may indeed have been due to an entirely different and still unexplained geodynamic perturbation and response mechanism involving coupling between the earth's core and mantle. It does not, however, rule out the gradual reduction in the mass balance of polar ice as the possible underlying cause for the secular trend in the earth's rotation rate. Indeed, Barnett (*7*) has shown that since 1900 the secular trends of changes in the rate of earth's rotation and displacement of the earth's pole of rotation are consistent with an approximately equal thinning of the Greenland and Antarctic ice sheets.

Hansen *et al.* also contend that the melting of polar ice has a negligible effect on the global mean temperature. The extent of this negative feedback is strongly dependent on the assumed vertical profile of the cooling effect. Our own estimate for this, we pointed out (*1*), might be in error by a factor of 3 or 4. The estimate by Hansen *et al.* is subject to the same uncertainty.

On the basis of data in (*1*) we estimate that 50×10^{15} kg of ice discharged into the ocean would cause a mean sea level rise of 13.5 cm. However, in making this calculation we neglected to account for the isostatic adjustment (elastic deformation) of the ocean floor to the change in mass of the overlying water. Since the ratio of the density of the upper mantle to the density of sea water is approximately 3 : 1, the observed change in eustatic sea level (relative to tide gauge stations that are referenced to geodetic bench marks) will be about two-thirds of the meltwater increase. The addition of 50×10^{15} kg of meltwater should therefore correspond to an observed sea level increase of only 9 cm.

Since our report (*1*) was prepared, other evidence has been reported that tends to substantiate the hypothesis that the polar ice caps are diminishing. A crude calculation based on the observed freshening of North Atlantic deep water between 1972 and 1981 reported by the Transient Tracers in the Ocean program (*8*) indicates that this is consistent with a uniform thinning of the Greenland ice cap equivalent to about 10 cm per year (*9*). Anomalous freshening and cooling in the Labrador Sea (*10*) and in Antarctic waters within the past decade have been reported as well (*11*), and contemporaneous geochemical studies of Weddell Sea water provide positive evidence of a significant admixture of ice sheet meltwater (*12*).

The prospect of unprecedented global warming over the next several decades due to increasing atmospheric concentrations of CO_2 and other trace gases and the resulting increase in mean sea level attributable to oceanic thermal expansion and melting of polar ice is a matter of great concern. Each of the indices discussed here, global mean SST, global mean sea level, the mass balance of the polar ice sheets, water mass characteristics, and the earth's spin rate and displacement of its axis of rotation, are physically linked and each can be systematically monitored. The National Climate Program is now planning such an improved monitoring program.

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